How to distinguish a molecule from an "elementary" particle?

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Chiral 2013

Oct. 27 – 29, 2013, BeiHang University, Beijing

- Definition of a "molecule" and an "elementary" particle?
- Only unambiguous in Quantum mechanics (or quantum mechanical scattering theroy)!

1. Morgan's pole counting rule (D. Morgan, Nucl. Phys. A543, 632(1992).)
   X(3872) as an example
2. Some remarks on the properties of $f_0(600)$ and $f_0(980)$.

It has been a longstanding problem for particle physicists to judge wether a particle is elementary or composite, from experimentally known cross-section or phase shift data.

In some special cases, it is however possible to solve the problem model independently, by counting the number of poles near a threshold, in an *s*-wave amplitude.

Any scattering amplitude can always be written as,

$$T = \frac{1}{M - ik} \tag{1}$$

and (resonance) poles correspond to the zeros of $M - ik$, and M can be expanded in powers of k^2,

$$M(k^2) = -\frac{1}{a} + \frac{1}{2} r_{eff}^2 k^2 + o(k^4) \tag{2}$$

where a the scattering length, r_{eff} the effective range parameter. When $r_{eff} \simeq R$, $M - ik$ only contains one zero near threshold.

On the other hand when there is a CDD pole weakly couples to this channel, there will be two poles near the threshold, $M(k^2)$ can be expressed as,

$$M(k^2) = \frac{k^2 - k_0^2}{g^2} + rescattering \;\; corrections \tag{3}$$

where g is small. In this situation, there appears a pair of poles on the k plane, which implies the occurrence of an elementary particle.

Using the pole counting method, it is found that X(3872) contains two poles near threshold. For this reason it is argued that X(3872) contains large $c\bar{c}$ component (O. Zhang, C. Meng, H. Q. Zheng, PLB 680,(2009),453).

The experimental discovery of X(3872)

Belle Collaboration, Phys.Rev.Lett.91:262001,2003.
Observation of a narrow charmonium-like state in the $B^\pm \to K^\pm X$, $X \to J/\Psi\pi^+\pi^-$, $M_X = 3872.0 \pm 0.6(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ MeV, very near the $M_D + M_{D^*}$ mass threshold. $\Gamma < 2.3$MeV. $\pi\pi$ produced from ρ decay.

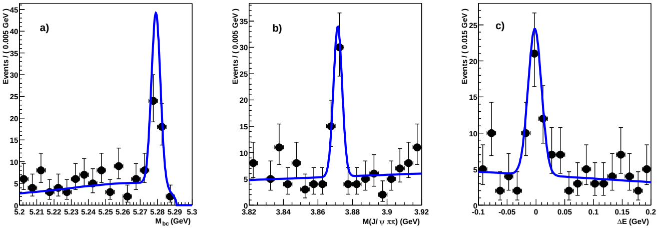


Figure: $M_{J/\Psi\pi^+\pi^-}$ invariant mass spectrum

$X(3872) \to J/\Psi\ \pi^+\pi^-\pi^0$ channel

K. Abe et al. (Belle Collaboration), hep-ex/0505037
$X(3872) \to J/\Psi\ \pi^+\pi^-\pi^0$ (from $J/\Psi\omega$):

$$\frac{\mathrm{Br}(X \to \pi^+\pi^-\pi^0 J/\Psi)}{\mathrm{Br}(X \to \pi^+\pi^- J/\Psi)} = 1.0 \pm 0.4 \pm 0.3\ , \tag{4}$$

Large isospin violation effects!

$X(3872) \to J/\Psi\gamma\ , \Psi'\gamma$

B. Aubert *et al.* [BaBar Collaboration], arXiv: 0809.0042 [hep-ex].

$$\frac{\mathrm{Br}(X \to \gamma J/\Psi)}{\mathrm{Br}(X \to \pi^+\pi^- J/\Psi)} = 0.33 \pm 0.12, \tag{5}$$

$$\frac{\mathrm{Br}(X \to \gamma \Psi')}{\mathrm{Br}(X \to \pi^+\pi^- J/\Psi)} = 1.1 \pm 0.4\,. \tag{6}$$

$X \to D^0\bar{D}^0\pi^0$ decays

G. Gokhroo et al. (Belle Collaboration), Phys. Rev. Lett. 97(2006)162002; B. Aubert et al. (BaBar Collaboration), Phys. Rev. D77: 011102(2008).

Upgraded in I. Adachi *et al.* [Belle Collaboration], arXiv:0810.0358 [hep-ex]:

$$M_X = 3872.6^{+0.5}_{-0.4} \pm 0.4\text{MeV} \ . \tag{7}$$

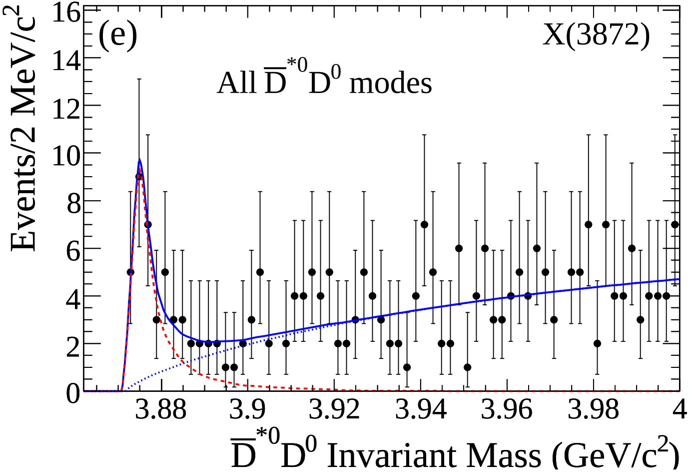
$$\text{Br}(B^+ \to K^+ X(D^{*0}\bar{D}^0)) = (0.73 \pm 0.17 \pm 0.13) \times 10^{-4} \ . \tag{8}$$

The upgrade comes from the inclusion of new data ($D^* \to D\gamma$), more sophisticated fit (unbinned fit with mass dependent resolution), and improved Breit–Wigner formula (the Flatté formula). The central value as given by Eq. (7) is still about 1MeV above the value measured by CDF Collaboration in the $J/\Psi\pi\pi$ channel:

$$M_X = 3871.61 \pm 0.16 \pm 0.19\,\text{MeV} \ , \tag{9}$$

which is slightly below the $D^0\bar{D}^{0*}$ threshold.
Peak position different in different channels.

In addition, BABAR (Phys. Rev. D77: 011102,2008) also gives new measurement on $X \to D^0 \bar{D}^{*0}$



Theoretical considerations

Q. Zhao, this conf...

1. D^0D^{0*} molecular bound state: N.A. Tornqvist, Phys. Lett. B **590**, 209 (2004); F. Close and P. Page, Phys. Lett. B **578**, 119 (2004); C.Y. Wong, Phys. Rev. C **69**, 055202 (2004);E. Braaten and M. Kusunoki Phys. Rev. D **69**, 074005 (2004); M.B. Voloshin, Phys. Lett. B **579**, 316 (2004); E.S. Swanson, Phys. Lett. B **588**, 189 (2004); **598**, 197 (2004).
   (large production rate of X(3872))
2. Normal $c\bar{c}$ state: C. Meng, Y.J. Gao and K.T. Chao, arXiv: hep-ph/0506222. M. Suzuki, Phys. Rev. D **72**, 114013 (2005).
   (mass so close to $D^0\bar{D}^{*0}$ threshold, accident?)
3. Dynamical complexity: couple channel effects, cusp, etc. (D.V. Bugg, e-Print: arXiv:0802.0934 [hep-ph])
4. Virtual state: C. Hanhart, Yu. S. Kalashnikova, A. E. Kudryavtsev and A. V. Nefediev, Phys. Rev. **D76**, 034007 (2007).

Flatté formalism

Essentially the same as Hanhardt et al., except the modification in the Breit-Wigner propagator,

$$D(E) = E - E_f + \frac{i}{2}(g_1 k_1 + g_2 k_2 + \Gamma(E) + \Gamma_c) \ , \tag{10}$$

Here subscript 1: $D^0 \bar{D}^{0*}$ channel; 2: $D^+ D^{*-}$ channel; $\Gamma(E)$ for $J/\Psi\rho$, $J/\Psi\omega$; Γ_c: all other channels. For more details, we refer to the papers.

Conclusions:
O. Zhang, C. Meng, H. Q. Zheng, PLB 680,(2009),453

1. First evidence in support of the existence of two nearby poles, if $\mathrm{Br}(B \to KX)$ reasonably small.
2. Strong indication that X(3872)=$c\bar{c}$ confining states heavily renormalized by $D^0\bar{D}^{*0}$ continuum.

Results supported by Kalashnikova, Nefediev, Phys. Rev. D80: 074004, 2009, in a different approach.

Two negative remarks:

1. May still be model dependent, e.g., parametrization form, dynamical model, etc..
2. A notorious counter example of instability: the $f_0(980)$.

An improved analysis on X(3872)

Modifying the Breit–Wigner (Flatte formula) resonance parametrization by including *both* molecular and $c\bar{c}$, let data determine howmany nearby poles. (M. Shi et al., to appear) (Achasov et al.; G. Y. Chen et al.)

$$
\begin{aligned}
\mathcal{L}_{D\bar{D}^*} &= \lambda_1(\bar{D}^{*\mu} D \bar{D}^{*\mu} D + \bar{D} D^{*\mu} \bar{D} D^{*\mu}) - 2\lambda_1(\bar{D}^{*\mu} D \bar{D} D^{*\mu})\,, \\
\mathcal{L}_{XD\bar{D}^*} &= g_1 X^\mu(\bar{D} D^*_\mu - \bar{D}^*_\mu D), \\
\mathcal{L}_{BXK} &= i g_2 X^\mu\,(\overline{B}\partial_\mu K \,+\, \text{h.c.})\,, \\
\mathcal{L}_{BKD\bar{D}^*} &= i g_3(\bar{D} D^*_\mu - \bar{D}^*_\mu D)\,(\overline{B}\partial^\mu K \,+\, \text{h.c.})\,,
\end{aligned}
\tag{11}
$$

Transverse part and longitudinal part contribution of massive spin 1 particle. Longitudinal part contribution is negligible near threshold.

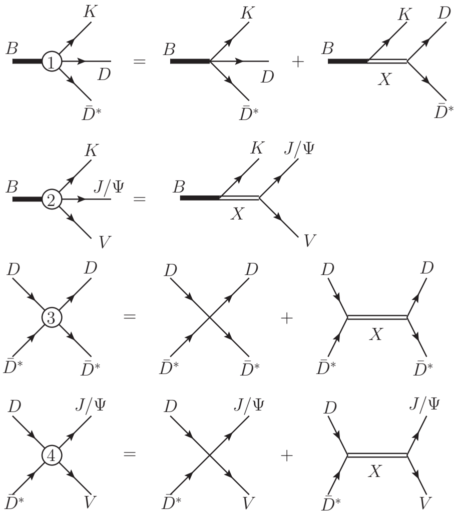


Figure: The decay pattern of $B \to \bar{D}^0 D^{0*}$ and $B \to J/\Psi\pi\pi$.

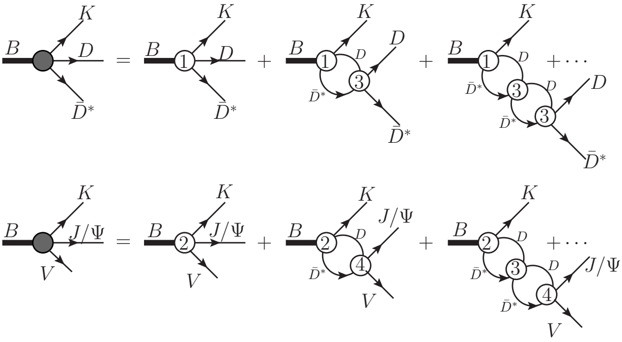
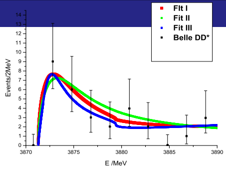
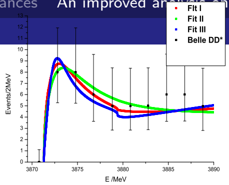


Figure: The effective "vertices".

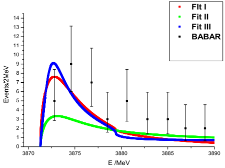
	Fit I	Fit II	Fit III
	$\chi^2/dof = 44.1/42$	$\chi^2/dof = 49.7/43$	$\chi^2/dof = 83.3/46$
λ_2	101.1±1.7	–	552.8± 1.1
c_0	–	–	$(17.0 \pm 0.1) \times 10^{-5}$
g_1	230±150	714±24	–
g_2/g_3	900±600	397±26	–
g_4	0.38±0.17	5.4±1.1	–
g_5	0.11±0.09	0.50±0.55	1.0 (fixed)
M_X	3871.6±0.9	3870.6±0.6	–
Γ_0	6.8±0.9	6.2±0.6	–

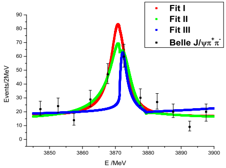
Table: Fit I: both X(3872) and $\bar{D}D^*$ contact interaction are considered; II: only X(3872) is considered; III: only contact interaction (bubble chain) is considered.

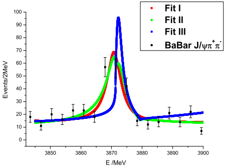




(a) (b)







(c) (d)

Figure: (a), (b): $D^0\bar{D}^{*0}$ invariant mass spectrum (BELLE), $\bar{D}^*$ from $\bar{D}^0\gamma$ and $\bar{D}^0\pi^0$, respectively; (c), $D^0\bar{D}^{*0}$ invariant mass spectrum (BABAR); (d), (e): $J/\Psi\pi^+\pi^-$ invariant mass spectrum for BELLE and BABAR data, respectively.

A few comments on $f_0(980)$

Renewed interests... (J. Pelaez, this conf...)
Confusions in the literature...
. "A Dispersive Analysis on the f0(600) and f0(980) Resonances in $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$ Processes" Y. Mao et al., PRD79(2009)116008 A K-matrix fit gives:

pole	sheet–II	sheet–III
σ	$0.549 - 0.230i$	$0.705 - 0.327i$
$f_0(980)$	$0.999 - 0.021i$	$0.977 - 0.060i$

Table: The poles's location on the $\sqrt{s}$–plane, in units of GeV.

Not quite stable

It has a tiny di-photon width (not a $\bar{q}q$ state):

	Pole-positions(GeV)	$\Gamma(f_J \to \gamma\gamma)$(keV)
$f_0^{II}(980)$	$0.999 - 0.021i$	0.12
$f_0^{III}(980)$	$0.977 - 0.060i$	0.35
$f_0(600)$	$0.549 - 0.230i$	0.76
$f_2(1270)(\lambda = 0)$	$1.272 - 0.087i$	0.66
$f_2(1270)(\lambda = 2)$		3.70

It also maintains some odd properties which is hard to understand:

pole position	$g^2_{\pi\pi}$	$g^2_{\bar{K}K}$
$\sqrt{s_{II}} = 0.999 - 0.021i$	$-0.07 - 0.01i$	$-0.10 + 0.09i$
$\sqrt{s_{III}} = 0.977 - 0.060i$	$-0.10 + 0.02i$	$-0.02 - 0.09i$

$f_0(600)$ also has a negative residue, but that seems to be well understood (see my talk at Chiral dynamics 09, Bern). (It's broad!) K– Matrix analysis for $f_0(600)$ can be refined using the production representation (PKU)

Further evidence in support of an odd $f_0(980)$

"On the scalar nonet in the extended Nambu Jona-Lasinio model"
M. X. Su et al., Nucl.Phys. A792 (2007) 288-305

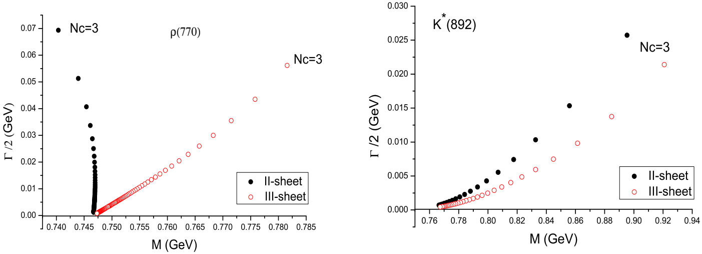
ENJL model + Heat Kernel expansion $\Rightarrow$ Effective chiral lagrangian in a linear realization.

With an unnaturally small Λ, and a bare $M_\sigma = 1GeV$. Using a K-matrix unitarization amplitude, one predicts the mass and width of σ ($f_0(600)$), κ ($K^*(700)$) and $a_0(980)$ simultaneously. No way to put the $f_0(980)$ in the game.

Here scalars are chiral partners of Nambu-Goldstone bosons, suggesting $f_0(980)$ may be different.

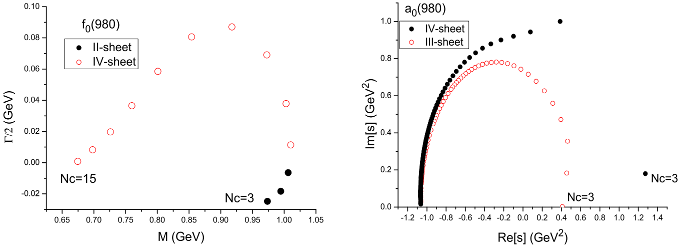
" Pole analysis on unitarized $SU(3) \times SU(3)$ one loop χPT amplitudes" Dai L.Y. et al., Commun. Theor. Phys. 58 (2012) 410-414

We analyze $\pi\pi - K\bar{K}$ and $\pi\eta - K\bar{K}$ couple channel [1,1] matrix Padé amplitudes of $SU(3) \times SU(3)$ chiral perturbation theory. By fitting phase shift and inelasticity data, we determine pole positions in different channels ($f_0(980)$, $a_0(980)$,$f_0(600)$, $K_0^*(800)$, $K^*(892)$, $\rho(770)$) and trace their N_c trajectories. We stress that a couple channel Breit–Wigner resonance should exhibit two poles on different Riemann sheets that reach the same position on the real axis when $N_c = \infty$. (Extended pole counting rule) Poles are hence classified using this criteria and we conclude that $K^*(892)$ and $\rho(770)$ are unambiguous Breit–Wigner resonances. For scalars the situation is much less clear. We find that $f_0(980)$ is a molecular state rather than a Breit–Wigner resonance, while $a_0(980)$, though behaves oddly when varying N_c, does maintain a twin pole structure.



(a)

Figure: N_c trajectories for ρ and K^*.



(a)

Figure: N_c trajectories for $f_0(980)$ and $a_0(980)$.

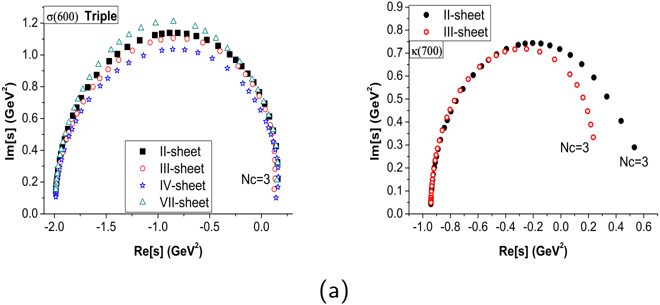


Figure: N_c trajectories for $f_0(600)$ and $K(700)$, in a 3X3 matrix Padé amplitude.

Conclusions on $f_0(980)$: No sound conclusion.

- Not like a $q\bar{q}$, neither a tetra quark
- Does not like to be in a chiral multiplet
- Prefer a molecule interpretation.

Thank you for patience!